

# **CONTROL, FILTERING AND PREDICTION FOR PHASED ARRAYS IN DIRECTED ENERGY SYSTEMS**

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## 1.0 SUMMARY

Under this project, University of California Los Angeles (UCLA) researchers have developed new methods for filtering, prediction and system identification in adaptive optics for high energy laser systems including phased arrays. The research has concentrated on wavefront prediction in digital holography. The methods developed can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems. The main contribution of the research is a state-space prediction filter that provides a near-optimal initial condition for image sharpening, thereby making image-sharpening and digital holography feasible in real-time adaptive optics.

## 2.0 INTRODUCTION

Digital holography has received increasing attention recently for a wide range of applications, including imaging through turbulent and turbid media, adaptive optics, three-dimensional projective display technology and optical tweezing [1–10]. The important promise of digital holography for all these application areas is the capability for wavefront reconstruction and correction without the bulky and sensitive optical hardware normally required for wavefront sensing.

The numerical methods of digital holography construct optical phase profiles from intensity information only. From the high-resolution image data that state-of-the art digital cameras and Charge-coupled devices (CCDs) can capture, digital holography can construct the entire complex field (amplitude and phase) of the optical wavefront, thereby yielding more information than do the commonly used wavefront sensors such as Shack-Hartmann sensors, without the optical hardware required for wavefront sensors.

Wavefront sensing hardware adds significant weight and size to optical benches required for existing system designs for missions that involve imaging, tracking and laser beam control; furthermore, wavefront sensors are plagued by the difficulty of maintaining the required alignment and focusing in dynamic mission environments on aircraft, ships and land vehicles. Digital holography has the potential to off-load the wavefront sensing function to digital computers, thereby making optical systems for a very large array of military and non-military systems much smaller, lighter, more robust to severe operating environments and more versatile.

A significant hurdle for digital holography in real-time applications such as high energy laser systems and high-speed imaging for target tracking is the fact that digital holography is computationally intensive, requiring iterative virtual wavefront propagation and hill climbing for image sharpening. Thus the computational burdens of current methods for digital holography entail latencies that severely limit the bandwidth of real-time wavefront sensing and correction.

UCLA research under this grant has developed advanced methods filtering, prediction and system identification in digital holography for adaptive optics. The research has concentrated on wavefront prediction to speed up image sharpening in digital holography. The methods developed can achieve significant improvements in on-target Strehl ratios and tracking jitter for phased-array high energy laser systems.

### **3.0 METHODS, ASSUMPTIONS, AND PROCEDURES**

#### **3.1 Methods for Wavefront Prediction in Digital Holography**

The primary methods used to design the predictor are the following:

- System identification
- Minimum-variance filtering and prediction

The primary methods used in digital holography are the following:

- Fourier optics
- Numerical imaging and wavefront interference

The following methods were used for image sharpening:

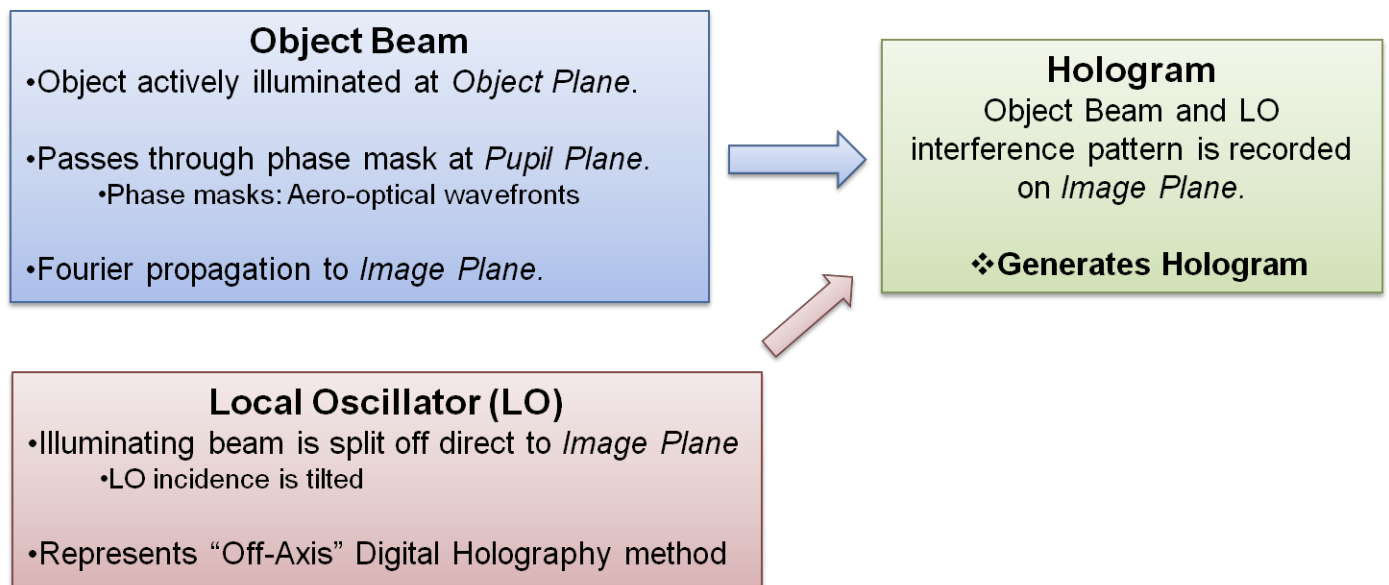
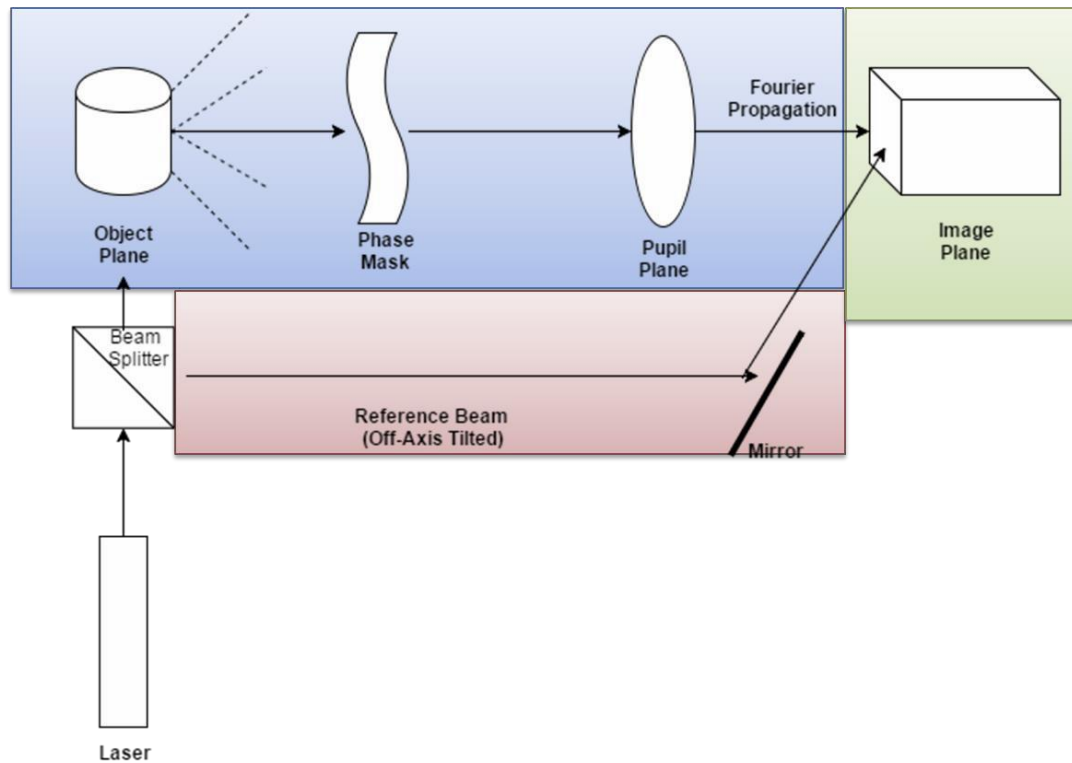
- Wavefront corrections represented as Zernike functions
- Numerical optimization of sharpness criteria

#### **3.2 Assumptions**

It is assumed that an image of an extended object propagates through atmospheric wavefront aberrations to yield a distorted image in the pupil of an optical measurement system.

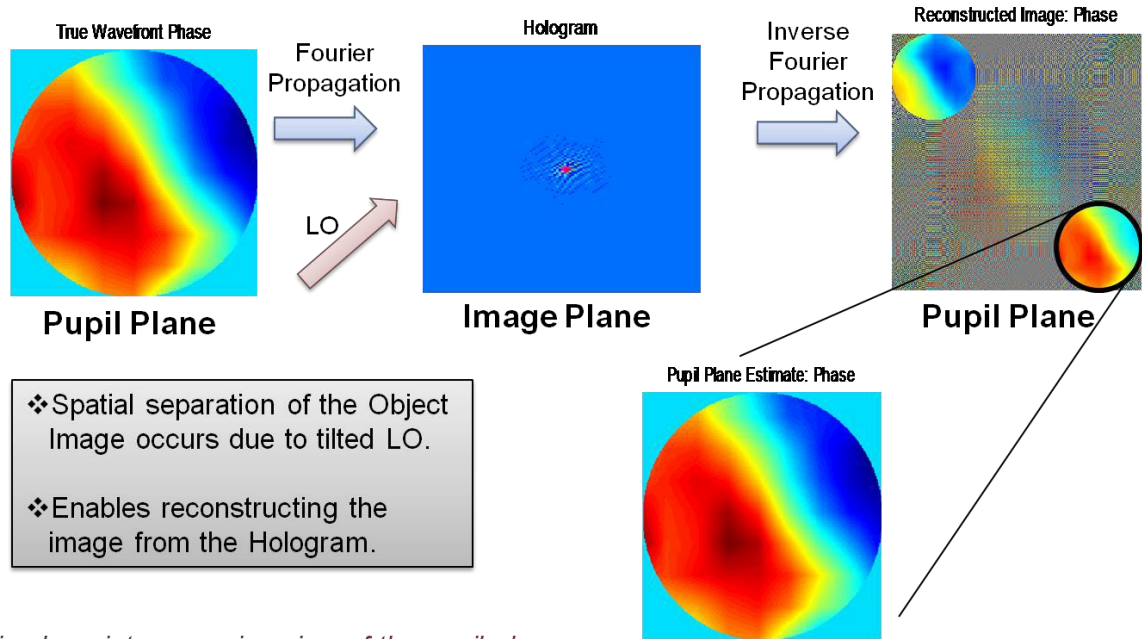
#### **3.3 Design, Analysis and Simulation Procedures**

The research procedure consisted of the following steps. A digital holography simulation, described in Figs. 1 and 2, was constructed, and aero optical wavefronts were used to produce aberrations in the optical complex field propagating from an extended object. An image sharpen algorithm was programmed to optimize wavefront correction represented as a linear combination of Zernikes. UCLA's subspace system identification method was used to identify an optimal prediction filter from sample data sequences of wavefront errors. This prediction filter was used to predict the starting wavefront correction for sharpening in successive wavefront correction. The digital holography simulation, system identification and image sharpening were performed by a collection of Matrix Laboratory (MATLAB) functions developed in the course of the project.



**Figure 1. Description of digital holography simulation.**





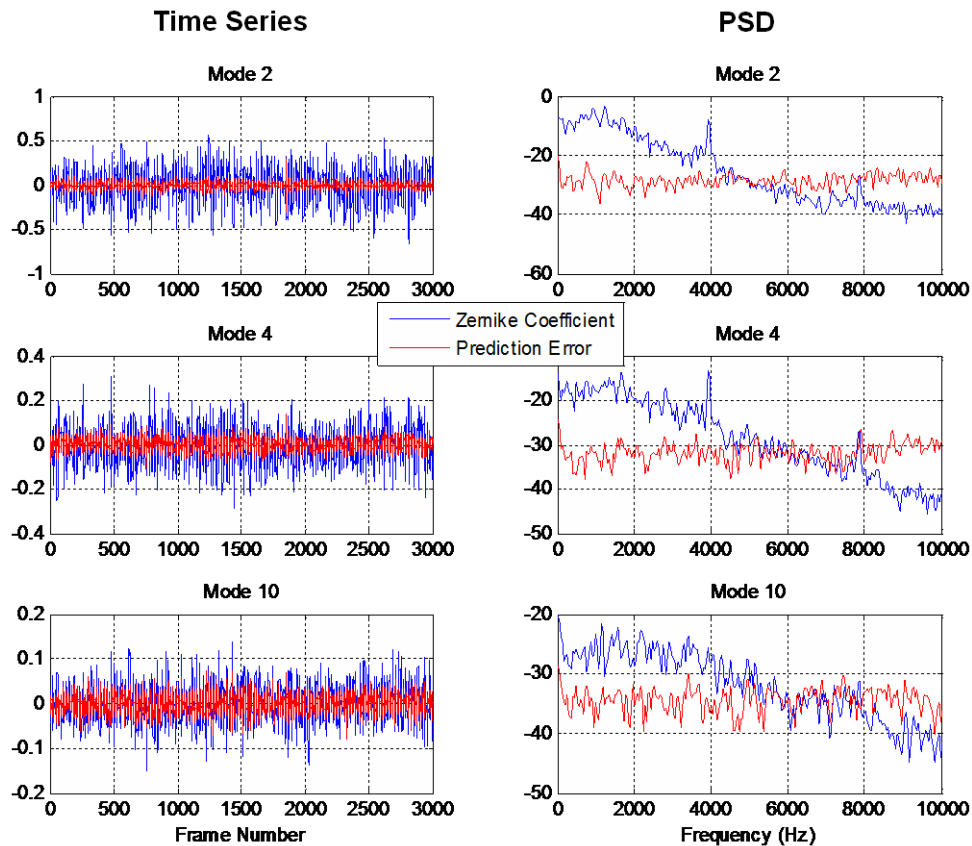
*Simple point source imaging of the pupil plane.*

**Figure 2. Point source imaging of the pupil plane in the digital holography simulation.**

## 4.0 RESULTS AND DISCUSSION

### 4.1 System identification and prediction for image sharpening

UCLA's subspace system identification algorithm was used to identify a minimum-variance prediction in state-space form from a sample sequence Zernike coefficients. This sample data sequence was generated by imaging the pupil plane (assuming a distant point source object) for sample sequence of 4000 aero-optical wavefronts. The identified prediction filter then was used for a second sequence of aero-optical wavefronts and extended image to predict the Zernike coefficients for the sharpening algorithm. Figure 3 compares the true Zernike coefficient sequences and the corresponding prediction error sequences for three representative Zernike modes and the sample wavefront sequences used for identification. That the prediction error sequences are very close to white (i.e., flat power spectra) shows that the prediction is indeed close to theoretically optimal.

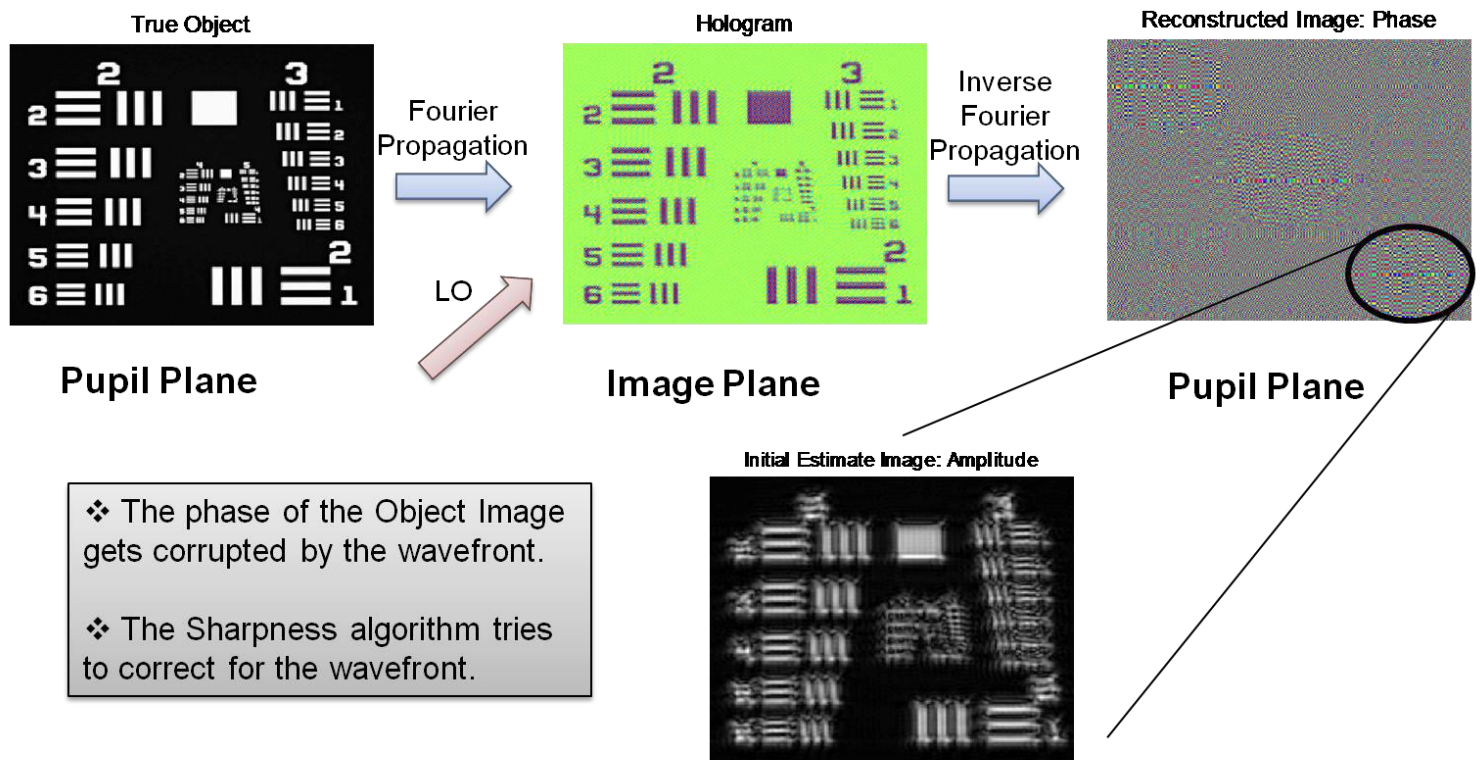


**Figure 3. Zernike coefficients and prediction errors for representative Zernike modes. Left: time series. Right: power spectral densities.**

## **4.2 Image sharpening and prediction**

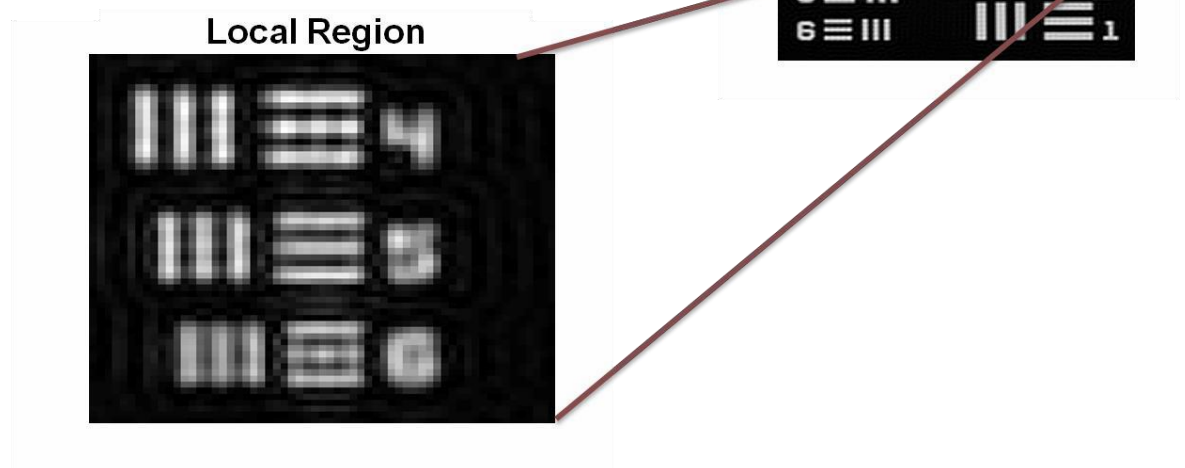
The following figures illustrate local image sharpening in the digital holography simulation for the Air Force bar chart. Results to date indicate that sharpening a local region in the detector plane is more effective than global sharpening and the prediction is more effective in local sharpening. Figure 4 shows the bar chart along with a typical pupil plane complex field reconstructed by digital holography.

Figures 5 and 6 show results for sharpening with and without prediction. The plots in Figs. 5 and 5 compare sharpening with and without prediction for fixed numbers of sharpening iterations. The criterion Sharpness (% Error) represents the percent of reduction in the sharpness objective from its value for an unaberrated image.



#### Local Correction Details:

- Full image: 256 x 256 pixels
- Region of Interest: 64 x 64 pixels
  1. Correct the ROI phase on Pupil Plane
  2. Propagate to Image Plane
  3. Sharpen the ROI on Image Plane

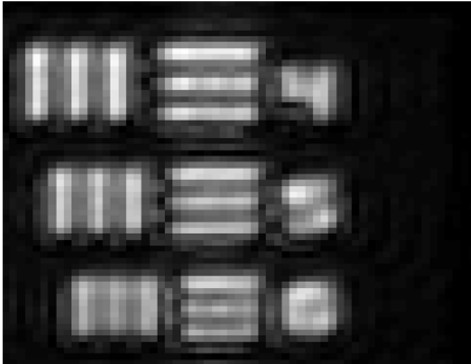


**Figure 4. Top: Air Force bar chart, reconstructed pupil plane complex field in the presence of wavefront aberration. Bottom: Description of local sharpening.**

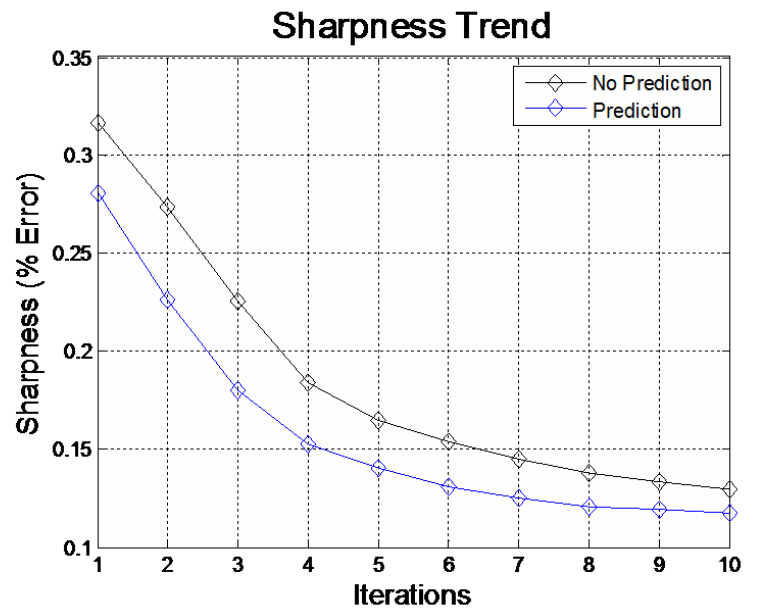
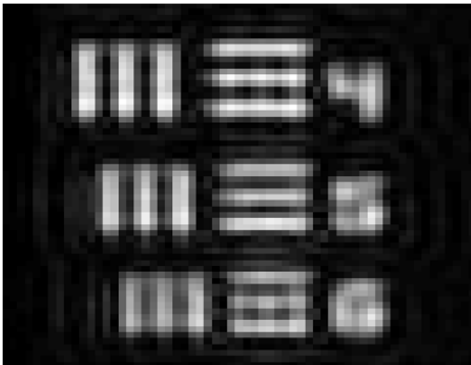
## *Light Aero-Optical Wavefront Error Sequence*

### Example Time Step

Uncorrected Image: Amplitude



Corrected Image: Amplitude

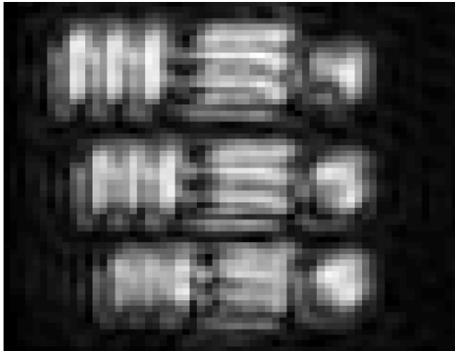


**Figure 5. Left: Focal plane image. Right: Comparison of image sharpening results with prediction and no prediction. Smaller % Error indicates better sharpened image.**

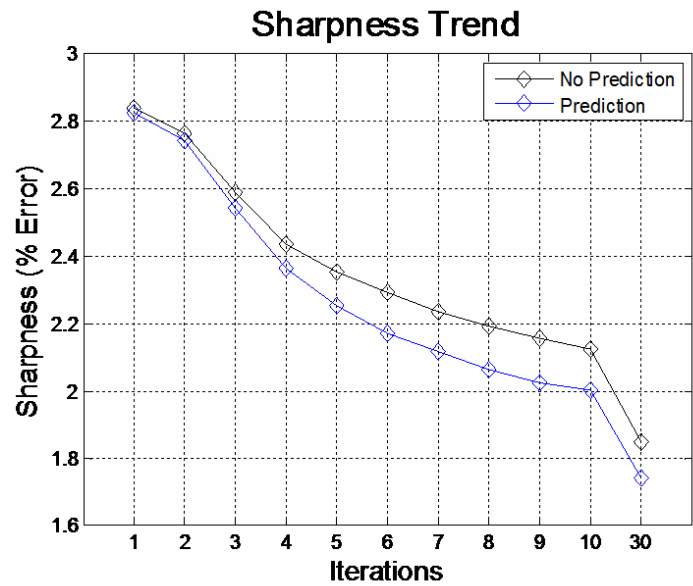
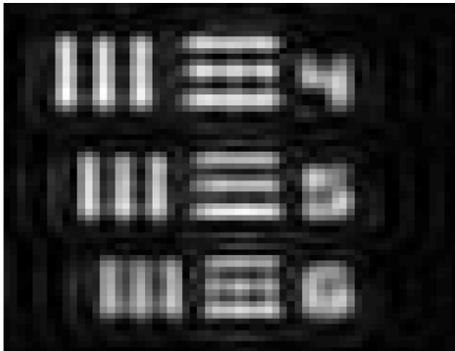
## *Heavy Aero-Optical Wavefront Error Sequence*

### Example Frame Instance

Uncorrected Image: Amplitude



Corrected Image: Amplitude



**Figure 6. Left: Focal plane image. Right: Comparison of image sharpening results with prediction and no prediction. Smaller % Error indicates better sharpened image.**

## 5.0 CONCLUSIONS

This project has developed new methods for filtering, prediction and system identification in digital holography for adaptive optics. Simulation results show that an identified prediction filter for the Zernike coefficients optimized in sharpening a sequence of aberrated images of an extended object reduces the number of sharpening required for iterations for each frame, thereby reducing the real-time computational burden. To date, simulation results indicate that sharpening a local region in the detector plane is more effective than global sharpening and the prediction is more effective in local sharpening.

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